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Experimental and numerical study on the compaction of granular soils by vibrations

Etude expérimentale et numérique du compactage de sols granulaires par vibrations

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ABSTRACT: The paper deals with the influence of vibrations, i.e. cyclic excitations with large acceleration amplitudes, on dry granular materials like sand. The inertial stresses induced by the accelerations cause a temporary loss of shear strength as well as a permanent compaction of the material. Although this phenomenon is known for a long time and plays an important role in many geotechnical construction processes like deep vibrocompaction and vibrodriving of piles, only few systematic studies on the fundamental relations exist. The investigations at TU Berlin focus on the relationship between the static and dynamic stress states in the material during vibrations and the achieved compaction. An experimental setup was developed which allowed for the compaction of sand under small effective stresses and large acceleration amplitudes. As the dynamic stresses determining the compaction behaviour vary within the sample, a simple method to evaluate the vertical distribution of void ratio is applied. The results of these tests are presented and a simple model for estimating the compaction based on the stress state and acceleration amplitude is proposed. This model is applied to the results of numerical simulations of deep vibrocompaction, to gain an estimate of the amount of compaction caused by the cyclic accelerations.

RÉSUMÉ: Ce document traite de l'influence des vibrations, c'est-à-dire des excitations cycliques avec de grandes amplitudes d'accélération, sur les matériaux granulaires secs comme le sable. Les contraintes inertielles induites par les accélérations provoquent une perte temporaire de la résistance au cisaillement ainsi qu'un compactage permanent du matériau. Bien que ce phénomène soit connu depuis longtemps et qu'il joue un rôle important dans de nombreux processus de construction géotechnique tels que le vibrocompactage en profondeur et le vibrofonçage de pieux, il n'existe que peu d'études systématiques sur les relations fondamentales. Les recherches menées à l'Université technique de Berlin se concentrent sur la relation entre les états de contrainte statiques et dynamiques dans le matériau pendant les vibrations et le compactage obtenu. Un dispositif expérimental a été mis au point pour permettre le compactage du sable sous de faibles contraintes effectives et de grandes amplitudes d'accélération. Comme les contraintes dynamiques qui déterminent le comportement du compactage varient à l'intérieur de l'échantillon, une méthode simple est appliquée pour évaluer la distribution verticale du taux de vide. Les résultats de ces essais sont présentés et un modèle simple d'estimation du compactage basé sur l'état de contrainte et l'amplitude d'accélération est proposé. Ce modèle est appliqué aux résultats des simulations numériques du vibrocompactage en profondeur, afin d'obtenir une estimation de l'ampleur du compactage causé par les accélérations cycliques.

Keywords: Vibrocompaction; granular soils; cyclic accelerations; experimental tests; numerical simulations.

1 INTRODUCTION

Granular material like sand can be efficiently compacted with the use of vibrations, which we define as alternating deformations of the grain skeleton and sufficiently large acceleration amplitudes. Although the first findings were published early on (Barkan, 1962), the underlying mechanisms are still poorly understood. There have been repeated attempts to investigate the phenomenon (Youd, 1968; Norman-Gregory and Selig, 1989; Bement, 1996; see also Denies, 2014 for an overview) but these have remained isolated and have not led to a systematic theory of vibrocompaction of granular materials. The experimental set-ups of the works mentioned are always comparable: A sample of granular material is placed inside a test container with rigid walls, loaded vertically via a load stamp and vibrated in vertical or horizontal direction using a shaking table. The change of density over time is determined by measuring the settlement of the load stamp.

Irrespective of the exact experimental set-up and the intensity or direction of vibrations applied, the following basic observations were made: Starting from the initial value e_0, the void ratio decreases nonlinearly and asymptotically approaches the limit value e_Γ (also called the equilibrium void ratio, Figure 1 above), which is defined as the minimum void ratio that can be achieved under the given surcharge p_z and non-dimensional acceleration amplitude $\Gamma = a/g$, where a is the acceleration amplitude and g is the acceleration due to gravity. With an increasing value of Γ the equilibrium void ratio e_Γ decreases towards the minimum void ratio achievable for this material by vibrations (Figure 1 below).

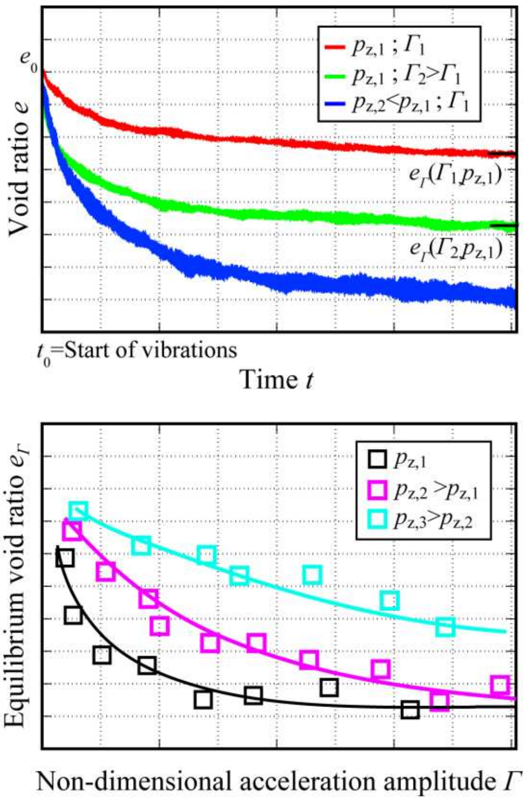

Figure 1. Time history of void ratio during compaction with constant surcharge p_z and dimensionless acceleration amplitude Γ (above). Dependence of the equilibrium void ratio e_Γ on the acceleration amplitude Γ (below).

Obviously the void ratio e_Γ isn't solely dependent on the acceleration amplitude but also the static surcharge p_z. It does not seem reasonable to use Γ as the only non-dimensional number characterising the compaction behaviour, as has been common practice up to now (Youd, 1968; Bement, 1996). Accordingly, a new non-dimensional number is introduced here, which we call the local stress ratio κ. It is defined as the ratio of the dynamic (destabilising) stress amplitude σ_{dyn} to the static (stabilising) stress σ_{stat}. For the specific test conditions applied in this study, it is assumed to take the form:

$$\kappa = \frac{\sigma_{\text{dyn}}}{\sigma_{\text{stat}}} = \frac{\Gamma \cdot g \cdot m/A}{p_z + g \cdot m/A} \quad (1)$$

where m and A are the sample's mass and sectional area respectively. The dynamically excited mass increases with the depth z of the sample (starting from the sample's top surface), so that κ is a function of z and increases with depth. It will be shown that the dimensionless number controlling densification is κ rather than Γ.

As the stress ratio defined in eq. (1) increases with depth and the equilibrium void ratio depends on κ, one hypothesis is that the distribution of void ratio inside the sample also correlates to the stress ratio, i.e. the density in the lower area of the sample is greater than in the upper area after compaction.

2 EXPERIMENTAL SETUP

The experimental setup depicted in Figure 2 is used for the tests carried out at TU Berlin. Here the sample is placed in a cylindrical container having rigid walls. The surface is straightened and covered by a load stamp. The specimen has a diameter of $d = 80$ mm and initial height h_{ini} ranging from 60 mm to 80 mm, depending on the installed mass and initial density.

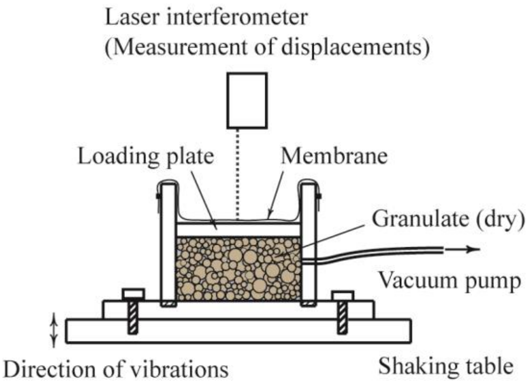

Figure 2. Experimental setup for vibrocompaction tests. The container is cylindric and has an inner diameter of 8 cm.

The container is then sealed by a thin latex membrane, so that an underpressure p_0 can be created inside the sample with the aid of a connected vacuum pump. It follows that the resulting static surcharge is given by $p_z = p_{\text{atm}} - p_0$.

On the one hand this way of load application makes it possible to create a very small static stress level so that even with relatively small accelerations a large value of κ can be achieved. On the other hand, the surcharge itself is not dependent on inertia, as would be the case for example, if the load was applied via weights.

The tested material was a Toyoura sand, with a coefficient of uniformity of $C_U = 1.3$, a minimum/maximum void ratio of $e_{\text{min}} = 0.569$ and $e_{\text{max}} = 0.907$ respectively. After placing the test cell on a shaking table, it was vibrated at a frequency of 50 Hz in vertical direction, where the acceleration can be regulated by adjusting the displacement amplitude.

In order to determine the local distribution of void ratio and to check on the hypothesis formulated in the introduction, the following simple procedure is applied: After compaction, the sample is removed in layers using a vacuum pump. Height and mass of each layer is measured so that the locally averaged void ratio can be calculated afterwards.

3 EXPERIMENTAL RESULTS

The distributions of the locally averaged void ratios after compaction e_κ over the sample height are shown in Figure 3. For reference an exemplary initial (i.e. pre-compaction) distribution is also shown in black. The average initial void ratio was around 0.9 in all of the tests, which is close to the sand‘s maximum void ratio.

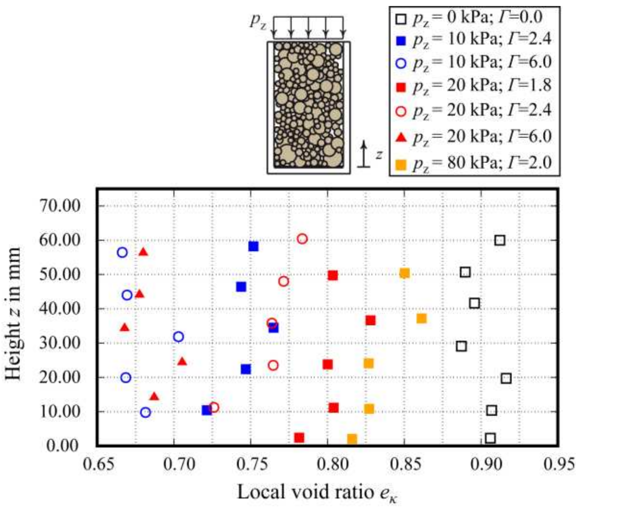

Figure 3. Distribution of void ratios after compaction over the sample height for various combinations of surcharge and acceleration amplitude.

Some already known properties can be identified: The larger the acceleration amplitudes (at constant surcharge), the more the sample is compacted over the entire height. The larger the surcharge, however, the weaker the compaction, given the same or comparable acceleration. There seems to be at least a tendency for the sand to be denser in the lower areas than in the upper areas, although this is not clearly pronounced in all cases. However, this is consistent with the observations by Norman-Gregory and Selig, 1989.

If these test results are plotted over the assumed local dynamic stress ratio κ, a correlation of both quantities is visible (Figure 4). The black curve in Figure 4 is given by equation (2), with the vibratory minimum void ratio $e_\infty = 0.65$, the maximum void ratio $e_{\max} = 0.907$ and a coefficient $\lambda = 0.015$:

$$e(\kappa) = e_\infty + (e_{\max} - e_\infty) \cdot \frac{1}{1+\kappa/\lambda} \qquad (2)$$

4 NUMERICAL SIMULATIONS

We will now demonstrate briefly, how these findings could be used to estimate the compaction of sand due to cyclic accelerations caused by vibroflotation, a well-established method for the compaction of granular (see Kirsch and Kirsch, 2010 for details). For this we use results obtained by simulations with the CEL method. The numerical model is shown in Figure 5.

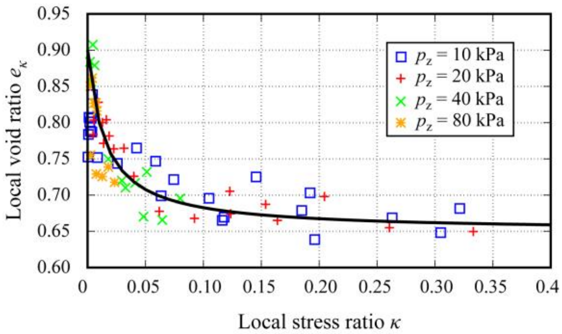

Figure 4. Dependence of the locally averaged void ratio after compaction on the local stress ratio, for which a linear distribution is assumed.

The mechanical soil behaviour is modelled using the hypoplastic constitutive model with intergranular strains (von Wolffersdorff, 1996; Niemunis and Herle, 1997) using the parameters shown in the table in Figure 5. The model and its validation were described in detail by Wotzlaw et al., 2023. It has a height of 30 m and a diameter of 25 m. In our simulations the vibrator is operating at a depth of 11 m below ground level (referring to the vibrator tip). The initial void ratio is given by $e_0 = 0.907$.

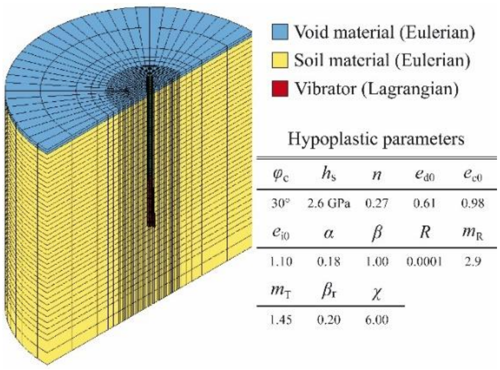

Figure 5. Numerical model and hypoplastic parameters after Herle (1997).

By using this fully fledged CEL model described above, the time history of vertical stress could be evaluated. From this and the local static vertical stress, a time-averaged local stress ratio has been determined for each finite element in order to apply eq. (2) (Figure 6). In a radial distance of approximately 1 m from the vibrator axis, the stress ratio has a value of up to 0.5 and then quickly decreases in a larger distance to the vibrator. However, as can be seen from Figure 4, the degree of compaction does not increase significantly for stress ratios larger than approximately 0.2.

Accordingly, the distribution of minimum void ratio due to vibrations in Figure 7, which we get solely by applying Eq. (2) on the distribution of average stress ratio, shows that the soil can be compacted efficiently from an initial relative density of $I_{\mathrm{D}} = 0$ to a densities after compaction ranging from $I_{\mathrm{D}} = 0.6$ in a distance of 3 m from the vibrator axis to $I_{\mathrm{D}} = 0.76$ within a radius of 1 m around the vibrator.

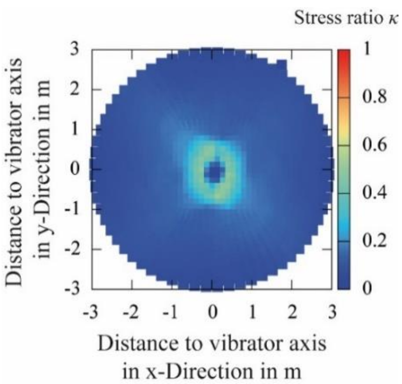

Figure 6. Average local stress ratio in a depth of 9.6 m below ground level caused by vibrocompaction.

5 CONCLUSIONS

We have shown experimentally, that the void ratio after vibrations e_κ depends on the local stress ratio κ inside the vibrated granulate. Further research on this matter has to be performed, especially the influence of the direction of vibration and the effect of vibrations on the shear resistance have to be considered.

We included numerical simulations to show how these findings can be used to estimate the amount of compaction solely by application of the proposed eq. (2). In later works, the effect of simultaneous cyclic shear deformations has to be included. However, even with all simplifications, this example shows that the impact of cyclic accelerations on the relative density of granular soils should be taken into account in numerical simulations. Utilising the dependence on the local stress ratio can be one way of doing so.

ACKNOWLEDGEMENTS

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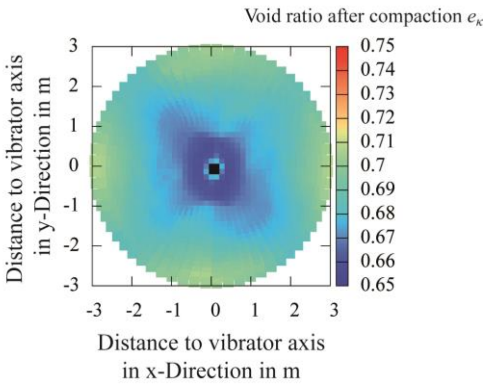

Figure 7. Minimum void ratio e_κ due to vibrations caused by vibrocompaction.

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